Computational Process Modeling for Additive Manufacturing

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A Cost-Share Project between OSU and NASA MSFC.

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Introduction / Review

- Industrial Relevance
  - Optimize material build parameters with reduced time and cost through modeling
- Goals of the project
  - Model microstructure evolution in a powder-bed fusion (PBF) additive manufacturing (AM) process, using thermal modeling from Applied Optimization (AO) and Simultaneous Transformation Kinetics (STK) modeling at OSU.
  - Validate model using metallography from coupons manufactured at the Marshall Space Flight Center (MSFC) Advanced Manufacturing Lab using a Concept Laser GmbH Cusing M2 system and in-situ data acquisition from QM Meltpool.
- Previously Presented
  - AO Process Modeling Results compared with single- and double-track samples
- In this presentation
  - Review AO Process Modeling results
  - Discuss STK microstructure evolution model
  - Lessons learned, challenges, conclusions and future work

Project Milestones and Timing

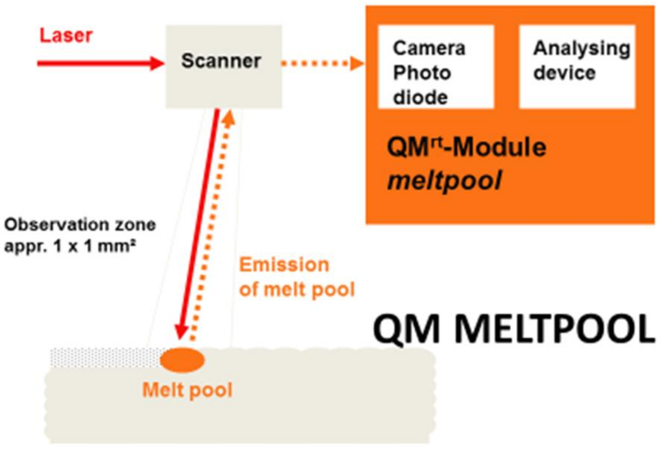
Date plan	Date Completed	Milestone/Deliverable	Status
7/30/2013	12/17/2013	Signed Space Act Agreement (NASA MSFC) and CIMJSEA Membership Agreement	100%
11/2013	1/3/2014	NASA will conduct single-track builds using powder-bed additive manufacturing and provide QM Meltpool Data to CIMJSEA	100%
12/2013	10/24/2013	NASA, AO and OSU will define coupon sample build parameters	100%
3/2014	10/25/2013	NASA will conduct coupon sample builds using powder-bed additive manufacturing and provide QM Meltpool data to CIMJSEA	100%
9/2014	10/31/2014	AO will provide Additive Manufacturing process modeling results for coupon builds[1]	100%
10/2014	12/23/2014	NASA will conduct metallography on coupon samples.	100%
4/2015	8/2015	OSU will report results from Simultaneous Transformation Kinetics models	100%
12/16/2015		Final Reporting of Results	30%

This slide modified to show Space Act Agreement milestones & deliverables.

[1]AO continued project after leaving CIMJSEA under a NASA STTR.

QM Meltpool

- MSFC invested in Concept Laser GmbH Quality Management (QM) modules on the M2 machine, which are marketed to provide process monitoring for a "quality-controlled fabrication process"
  - *"Quality management (QM) modules make it possible to ensure and document optimum component quality"* – concept-laser.de
- QM Meltpool monitors the molten area during a scan. Data from this module is intended for post-process inspection to ensure conformance to a reference build
- A high-speed IR Camera measures the integrated intensity of the radiation and captures images. Software determines from camera images how many pixels are within a threshold color level corresponding to molten material
- A Photodiode measures the brightness intensity of the melt pool



Part	Layer	Contour	Diode Intensity	From Photodiode, average intensity value of contour trace
			Meltpool Intensity	From Camera, average integrated IR intensity of contour trace
			Meltpool Area	From Camera, average number of pixels above threshold color level during contour trace
		Plane	Diode Intensity	From Photodiode, average intensity value of bulk material / hatch scan
			Meltpool Intensity	From Camera, average integrated IR intensity of bulk material / hatch scan
			Meltpool Area	From Camera, average number of pixels above threshold color level during hatch scan

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QM Meltpool Results - Challenges

- This project intended to use QM Meltpool results to validate thermal models, however, problems arose with this approach:
  - PI was unable to translate the QM Meltpool data to quantitative values relevant for validating models, without the use of supplementary thermal measurements which are still to-date unavailable. Calibration of the QM software is not an option based on OEM response.
  - The models are not fully developed at the time of this project's completion, and do not have results to validate.

Observation Area?

Is Gray Value calibration correct?

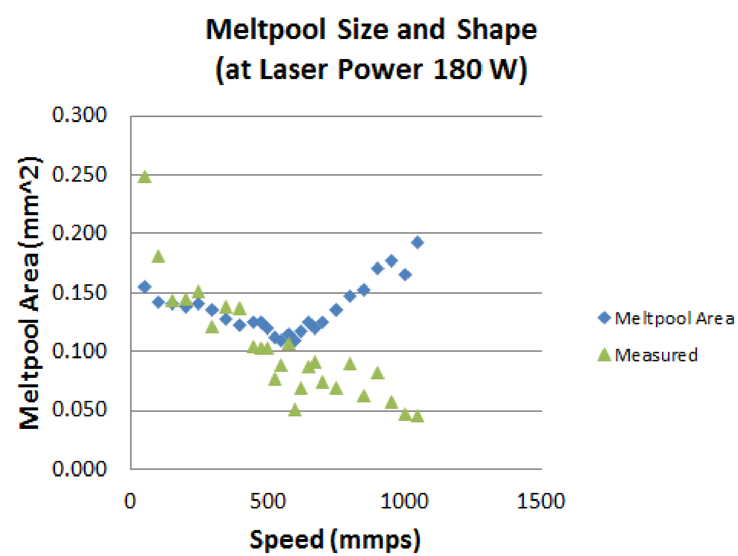
Field Of View?

Focal Length?

No ability to evaluate or reprogram FPGA

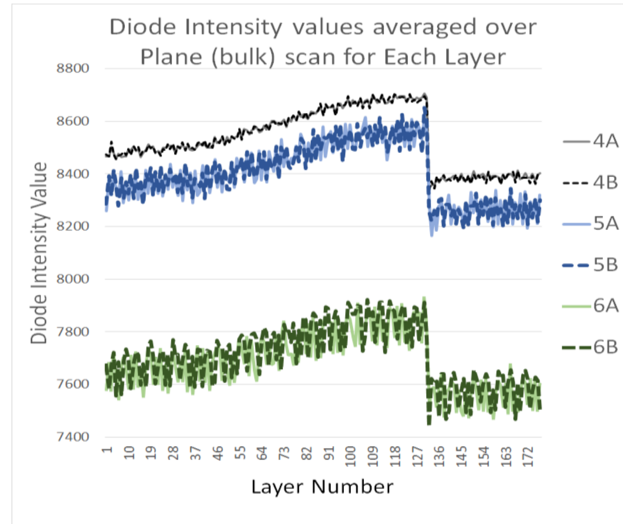
Melt Pool Images are not available

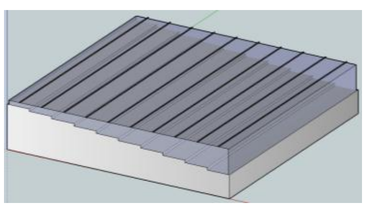
Is all melt area captured in frame?

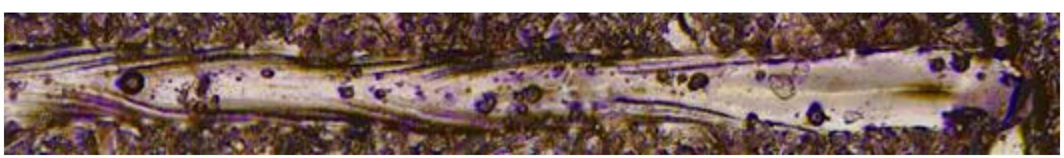


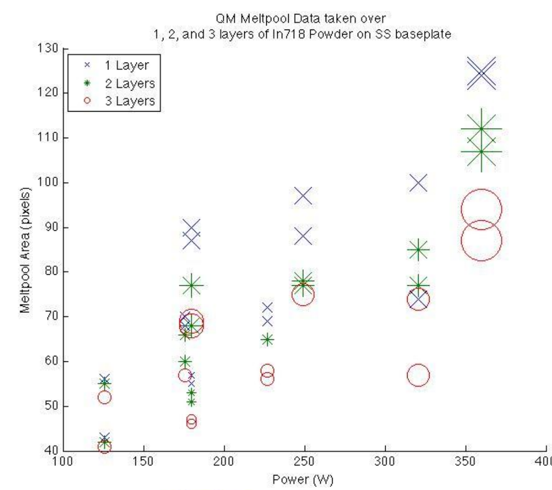
QM Meltpool Results - Opportunities

- Qualitative data from QM Meltpool has, however, been useful in determining heat inputs of components relative to one-another. This is shown in the single-track results, and used for other research conducted by the PI.
- Diode intensity was shown to be highly linear with power.
- Possible transition zone where weld breaks into multiple pools observed on speed chart (shown on previous chart)









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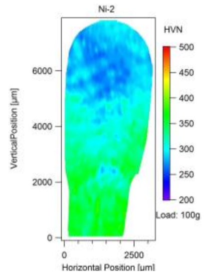
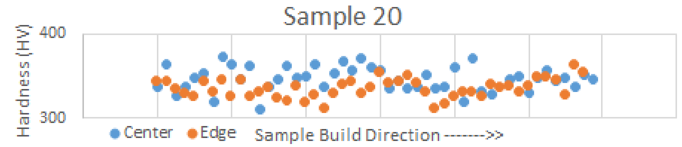
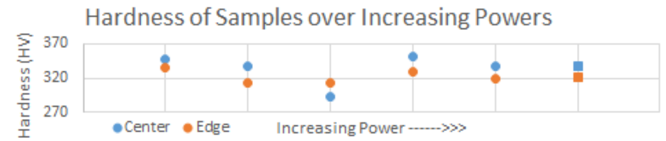
Metallography - Challenges

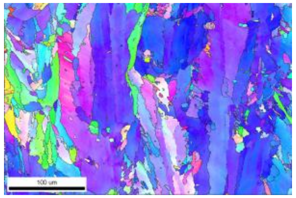
- Previous work identified microstructure changes over layers or parameters through hardness testing; testing several of the PBF samples revealed that hardness and as-built microstructure did not change significantly due to parameter variations.
  - This observation is consistent to that found in Song's study of IN718 built in a EOS machine.
  - PBF is orders of magnitude different than LENS- the heat input is significantly lower, and areas do not dwell in the aging temperature range.
- Previous studies also used EBSD. Inverse Pole Function and Orientation Deviation map of current samples revealed texture and strain. These results are expected, but not relevant to the modeling which utilizes thermal history as an input and outputs phase fraction.
- Future work should focus on quantifying phase fractions, using phase extraction techniques, in order to relate to modeling efforts.



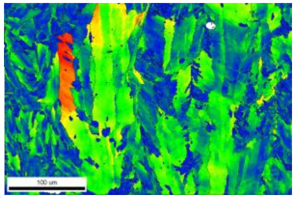
Hardness testing of LENS sample shown to the left (Makiewicz 2013); compare with PBF results 1) Across a single sample, and 2.) Sample averages over varying parameters.





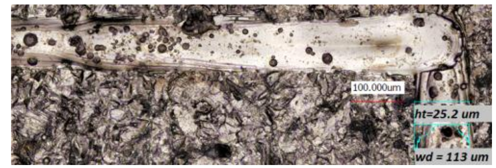


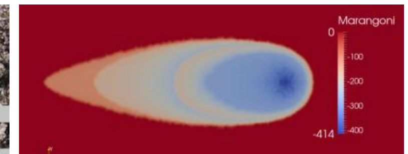
IPF and Orientation Deviation maps of a representative sample (Brown)

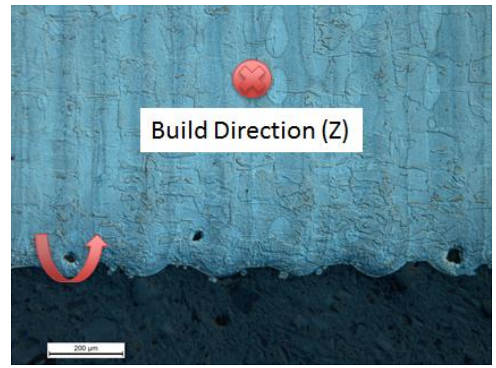


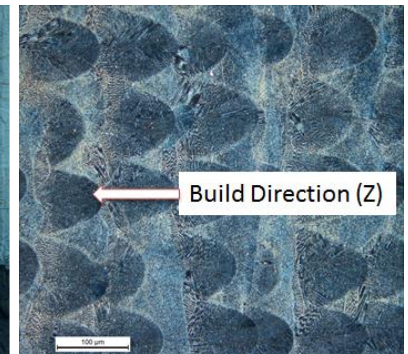
Metallography - Opportunities

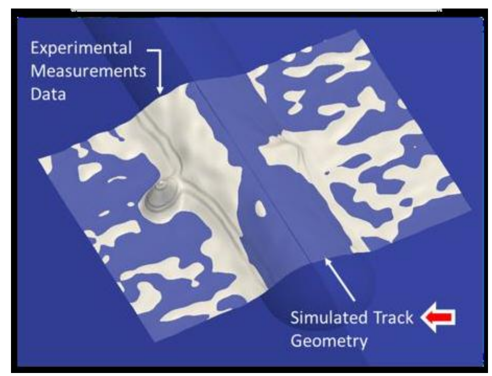
- Optical microscopy led to an understanding of how the weld pool shape changed over varying parameters, and allowed comparison to weld pool modeling.
  - Additional work completed, shown in following slides
- Optical microscopy also helped identify characteristic defects which can be evaluated in the physics-based models.
- Keyence Laser Confocal Microscopy allowed characterization of the weld bead crown – which can also be compared with AO models.







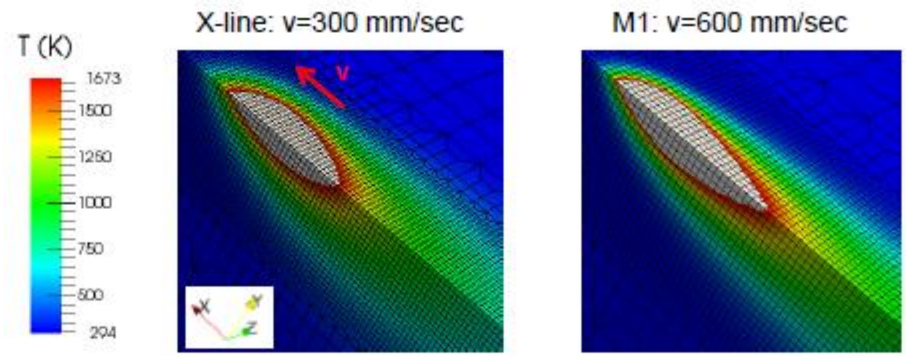




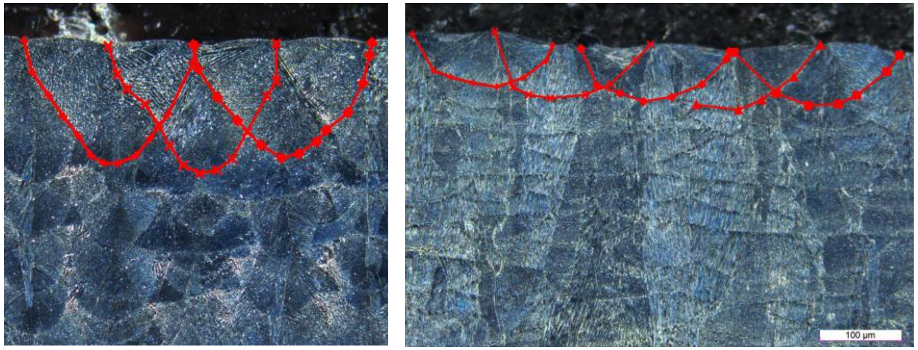
Top: Image and AO simulation of weld bead.
Mid: Optical microscopy; 1) DIC, showing characteristic meander defect, 2.) DF, showing characteristic scallop shape.
Bottom: AO comparison of measured vs. simulated weld crown, STTR for NASA.

Weld Pool Modeling

- AO, NASA Langley, and others are conducting weld models to predict the shape of the molten pool given incident laser parameters.
- This is helping NASA MSFC define parameters to achieve desired weld pool shapes and depths to combat lack-of-fusion defects or potentially deleterious grain growth.
- Solidification or thermal (heat dissipation) modeling may also aide in determining the weld pool shape that will be required for the desired microstructure.

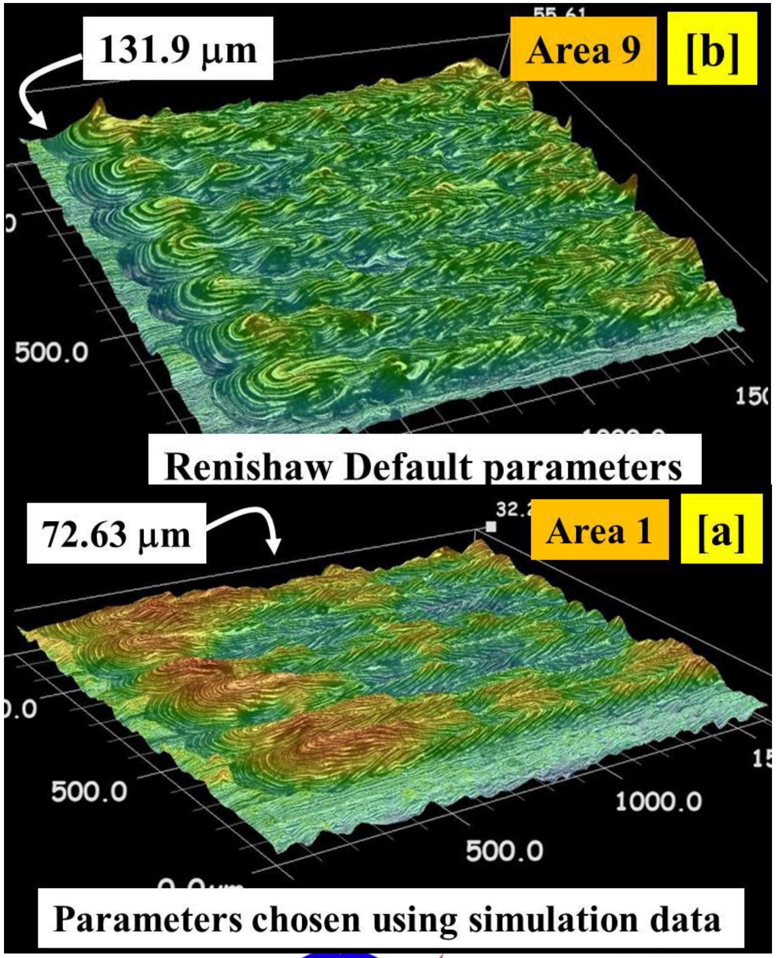


PREDICTED/ACTUAL	DEPTH (mm)	WIDTH (mm)
M1	0.034/0.152	0.108/0.209
XLINE	0.019/0.065	0.119/0.188
RATIO	1.8/2.3	.9/1.1



AO Layer Defect Modeling

- AO is continuing working with NASA through a Phase II STTR. Kickoff meeting was held 7/10/2015.
- Focusing on using physics models to minimize porosity & other defects.
- Process Parameters→ Track Dimensions→ Hatch Spacing→ Build Layer
- Currently working with UT for empirical sample build and evaluation using a Renishaw machine.
- Currently showing reduction in defects in 1 layer to be ~50% of defects realized in default parameters.



Images from Applied Optimization

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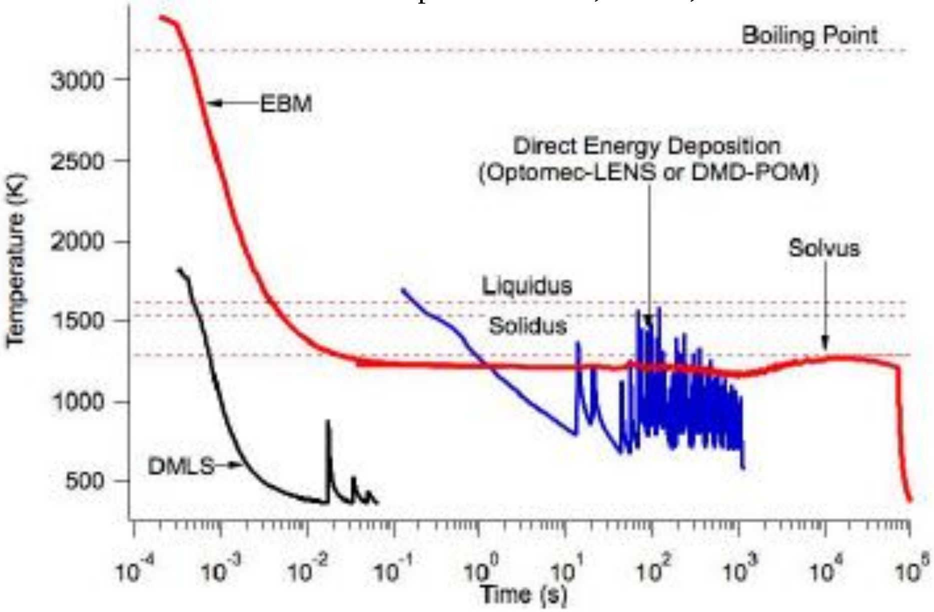
AO Thermal History Modeling

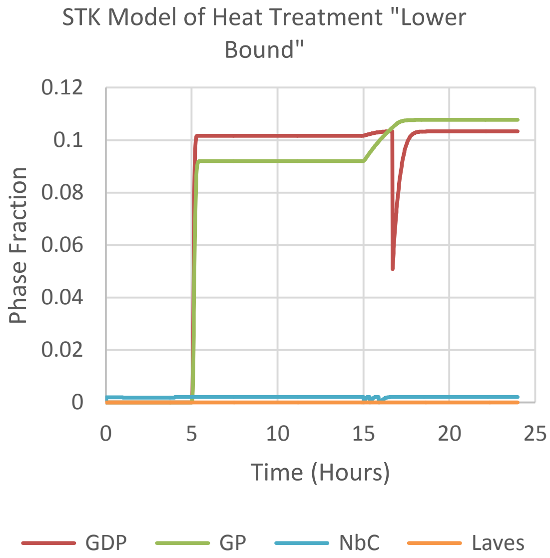
Thermal Histories at a point in EBM, LENS, and DMLS



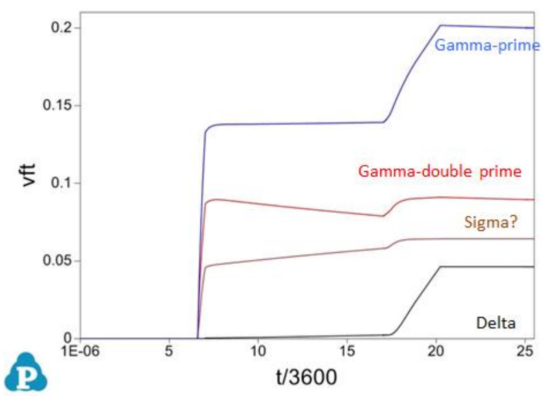
- AO determined a thermal history diagram as shown to the left for the PBF process (DMLS)
- This process is far unlike the other Additive Manufacturing Processes evaluated (EBM and LENS)
  - For EBM and LENS, the material stays near the aging temperature range while building
  - This allows the potential opportunity to design parameters for a final desired microstructure as-built, without heat treatment
  - This opportunity is not available for PBF, due to the orders-of-magnitude differences in time-scales and thermal gradients.

STK Modeling

- **Challenges:**
  - STK modeling of as-built material was not attempted due to limited data of (1) calculated thermal history for DMLS, and (2) experimental phase fractions.
  - Instead, an attempt was made to model the microstructure evolution during heat treatment, for which there were modeling results by Sudbrack (MS&T 2015) using CompuTherm Pandat.
    - STK model, calibrated using data from LENS, did predict formation of γ” and γ’; each about 10% at the end of heat treatment, which were comparable to Pandat predictions.
    - On the other hand, sigma and delta phases were not predicted as they were not considered in the current STK model.
  - Further improvement of STK model for IN718 DMLS and heat treatment was out of the scope of this project.
- **Opportunities:**
  - Modeling can help aid the optimization of heat treatment for DMLS material
    - Can be used to address solutionizing detrimental phases (Laves – observed in Song’s work, or Delta – observed in MSFC work), or precipitating strengthening phases
    - Phase evolution modeling has been useful in determining the root cause of some abnormal test specimens at MSFC



Pandat Model of Heat Treatment “Lower Bound”



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Project Challenges

- AM Process: Previous projects investigated LENS, and these models are not useful to DMLS
  - Orders of magnitude different speeds, gradients, sizes; Different dominating physics
  - Much greater ability to relate to, and control, microstructure in LENS process
  - IN718 will be heat treated in any scenario, so only goal for build parameters is to generate a fully consolidated material; the initial microstructure will have a limited effect on the post-heat-treated microstructure.
- Excessive number of DMLS Variables
  - Definable vs. undefinable, relevant vs. not relevant. Difficult to provide a thorough evaluation.
- Excessive project scope
  - 3 projects: 1.) Weld pool, 2.) Thermal History, 3.) Microstructure or material model
  - Scope was greater than previous projects under assumption that these projects could be leveraged
    - Process models could not be leveraged so AO, NASA and other STTR's were leveraged for process modeling
    - STK model needs development for DMLS, but MGI modeling at GRC can be leveraged for heat treatment studies
- Much of the material characterization was not directed/intentional – discovery research
  - Led to a lot of material characterization that did not yield any useful results
  - Was unclear how to tie material characterization to modeling effort
- AM is progressing fast enough that material samples built at beginning of project were obsolete or irrelevant after several months
- Bottom-line: **Complex physics for DMLS; Models are evolving and not yet turnkey solutions; However, they have helped advance the understanding of DMLS process and microstructure.**

Project Benefits

- MSFC became involved in the NASA Materials Genome Initiative
  - Initially this project was the only MGI project at MSFC, but our involvement has since expanded to include in-house thermal process modeling and a proposal to develop solidification modeling, as well as material thermo-physical property testing to support all NASA MGI PBF models
  - Glenn Research Center became involved in modeling heat treatment using JMatPro and Pandat (Chantal Sudbrack)
  - Ames Research Center was modeling laser interaction with powder particles and is currently the technical point-of-contact for the Applied Optimization STTR
  - Langley Research Center initiated in-house thermal process model development
- NASA Sponsored three STTR's in the subject of AM process modeling
  - CFDRC (COR at MSFC), Applied Optimization (COR at ARC), and MLPC (COR at LaRC)
- MSFC became members of the Additive Manufacturing Consortium
- MSFC collaborating with the University of Louisville due to interest in process modeling (Brent Stucker 3DSIM)
- MSFC worked with UTK on sponsored project proposal, which helped UTK join CIMJSEA/Ma^{2}JIC. MSFC plans to sponsor consortium with funding.

Project Completion

- Report will be provided by 12/2015 to summarize results
- NASA will continue to be involved in CIMJSEA / Ma^{2}JIC through sponsoring a UTK project

Questions?